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Cryogenic Power Conversion for Fuel Cell Systems, especially for Vehicles

A. Title: Cryogenic Power Conversion for Fuel Cell Systems, especially for Vehicles

B. Cross-References to Related Applications

A provisional patent application entitled "High-Efficiency Power Conversion for Fuel Cell Systems, especially for Vehicles" was filed on 3/15/2000. PPA Application number: 60/189,406, March 15, 2000.

A patent application (09/658,719) entitled "High-Efficiency Integrated Motor-Drive System" was filed on September 9, 2000.

C. Statement Regarding Federally Sponsored Research and Development

LTE was awarded an NSF SBIR contract entitled "Cryogenic Gradient Amplifiers for Magnetic Resonance Imaging (MRI)" in 1997.

MTEK/LTE has been awarded a six-month Phase I SBIR by DoD-BMDO entitled "High-Voltage Cryo-Inverter" (June 15, 2001).

D. References to a "Microfiche Appendix": None

E. Background of the Invention

1. Technical Field of the Invention

This invention relates to high-efficiency (>99.5%) power conditioning electronics used to convert the DC output of fuel cells into suitable AC power, especially useful for applications in vehicles such as buses, trucks, and ships.

2. Description of Related Art

Prior art is given by the existing technologies for transportation based on combustion engines. A worldwide effort is underway to implement new, environmentally cleaner means of transportation by converting to electric propulsion. Fuel cells are considered for this application.

F. Brief Description of the Invention

According to news reports [1] General Motors developed a car called "Zafira" which operates on fuel cells powered by liquid hydrogen, which has a cryogenic temperature of 20.27 K (–252.88 °C). Other fuel cells use a reformer which extracts hydrogen gas from natural gas (methane, CH_4) or gasoline [3, 4]. Alternatively, liquid natural gas (LNG) at a temperature of –161.5 °C (112 K) presents interesting possibilities which will be part of this invention disclosure.

Fuel cells deliver DC power, which is then converted by so-called inverters into AC power required for general use and for the efficient operation of electrical motors. These inverters are often larger, heavier, and more expensive than the motors they control.

The new concept of Cryogenic Energy/Power Conversion (CEC, CPC) has achieved drastic reductions in size, weight, and cost in the field of power electronics (Cryo-Micro-Power, CMP). Such size and weight reductions are nowhere more important than in vehicles, where energy savings are crucial. However, when applied to motor drives for transportation (or other) applications, CEC presents a major problem: the cooling, which adds further weight and requires an additional tank. This problem is solved in the case where a cryogenic fuel such as liquid hydrogen or liquid natural gas are already available, opening up interesting possibilities.

On the other hand, CEC can achieve its full potential only if implemented in the form of Cryo-Multichip Modules (CMCM) made with the wireless High-Density Interconnect (HDI) technology [P6,11,12,13]. This technology interconnects power transistor/diode chips in a half-bridge or full-bridge topology with polymer and metallic thin-films, thus eliminating the weak link in power electronics: the wire bond connections. Wireless interconnection provides many advantages such as higher switching speeds, higher frequencies, and improved efficiency and reliability.

The great potential of silicon applications in power and energy conversion (solid-state transformers, inverters, etc.) has not yet been adequately addressed by the semiconductor industry. It is desirable to change this situation by promoting the concept of cryogenic energy conversion, discussed in greater detail below. Furthermore, CMCMs are most important in transportation systems, and will be the key component for realizing Cryogenic Energy Conversion. An application example is described in the following pages. Systems can be optimized by combining CMCMs with High-Temperature Superconductors, especially when used to implement small filter inductors.

The widespread application of electric vehicles requires the development of a sufficiently small, light, and efficient motor drive or Adjustable Speed Drive (ASD) to couple the fuel cell or battery output to the motor. Therefore multichip modules are proposed for an efficient motor drive system based on the following assumptions and suggestions:

- Sooner or later, High-Temperature Superconductors (HTS) will be commercially available for applications in the power and energy generation and distribution fields at competitive prices: HTS cables, HTS transformers, HTS motors, HTS generators, etc. Billions of dollars have already been invested in this new HTS technology since its discovery in 1986.
- HTS components require Cryogenic Cooling. In most cases, such as in HTS cables and transformers, liquid nitrogen (LN2), at a temperature of 77 K (-196 C), will be used.
- The availability of HTS components requires a rethinking and redesigning of many energy systems. HTS Technology can best be supported by the new concept of Cryogenic Energy Conversion (CEC) based on Low Temperature Electronics (LTE) and Cryo-MOSFETs, Cryo-IGBTs, or other cryogenically operated devices.
- CEC can provide a considerable improvement in power and energy conversion efficiency as well as a drastic reductions in size, weight and, therefore, cost: Micro Cryo-Power. CEC represents the mating of High-Temperature Superconductors with Low-Temperature-operated Semiconductors. Electronic efficiencies of >99.5 % should be possible (not considering the

cooling penalty).

- The efficiency of electrical motor operation can be drastically enhanced by applying CEC to Motor Drives or ASDs. CEC would miniaturize these drives, which can be 2-3 times more expensive in prior art technologies, and are also much larger and heavier than the motors they control.
- Size and weight reduction, along with improved conversion efficiency, is nowhere more important than in transportation vehicles. Every kilogram of weight reduction translates into a considerable energy saving for vehicles traveling hundreds of thousands of miles in a lifetime.
- The push for higher efficiency leads to a push for electric vehicles requiring motors and ASDs.
- Great progress has been made recently (New York Times, Oct. 21, 1997) in the field of Fuel Cells using gasoline or Liquid Natural Gas (LNG: 112 K, -161 C).
- Therefore, this invention describes an ultra-small and light-weight Cryogenic Adjustable Speed Motor Drive in the power range of 50 to 200 Hp (35 to 150 kVA) using Cryo-MOSFETs or other suitable devices such as IGBTs.
- Tremendous commercialization opportunities providing higher energy conversion efficiencies can be envisioned for many transportation systems combining (H_2, O_2) fuel cells using LNG, LH_2, HTS motors, HTS cables and Cryo-Motor-Drives.
- In the case where HTS motors are used, the small cryo-power electronics can be integrated inside the HTS motor or onto the case of the HTS motor.

Motor drives using Cryo-Multichip Modules (CMCM) are intended for application in vehicles (buses, trucks, trains, ships, airplanes) as one important component in the coming age of Cryogenics which will combine High-Temperature SUPER-Conductors with Low-Temperature SEMI-Conductors. Such Adjustable Speed Drives (ASDs) will, of course, find applications in stationary systems as well. Many manufacturing plants requiring ASDs already use liquid nitrogen for other purposes. The proposed CMD will provide smaller size, reduced weight and increased efficiency due to its application of the new concept of Cryogenic Energy Conversion (CEC). Every kilogram of weight reduction translates into a considerable fuel saving over the lifetime of a vehicle running hundreds of thousands of miles. Such a development should be desirable in view of the fact that the federal government now mandates that cities of certain sizes must provide alternatively-fueled methods of public transportation ("Cold Facts", Summer 96 Issue).

Nothing beats semiconductor technology as far as reliability and reductions in size, weight, and cost are concerned. It is finally time to apply this technology to the field of (high) power conversion. This is made possible by the concept of Cryogenic Energy Conversion (CEC).

A press release of August 1, 1997 reads as follows: "Governor Pataki Announces Bond Act Funding for Clean Buses". Also: "Governor George E. Pataki today announced the State will award $3 million for the purchase of 39 clean-fuel buses as part of the Clean Fuel Bus Program under the Clean Water/Clean Air Bond Act." These hybrid buses use CNG (compressed natural gas) to fuel a Diesel engine. They are described in an article by King et al., in the IEEE Spectrum

of July 1995 [6] which presents the prior art. His figures [6, p. 29] show how small the motor is compared to the inverter motor drive.

The next step in the development of the electric transit bus could be the use of fuel cells to replace the diesel engine as a power source. Many companies are working to develop such fuel cells. Very interesting possibilities exist in the application of the new fuel cell technology. For large vehicles such as buses, LNG (liquid natural gas) is desirable, and makes the task of applying fuel cell technology easier. CVI, Inc. has successfully designed and manufactured on-board LNG fuel systems for buses such as those used by the Houston, Texas, METRO transit coach system.

G. Brief Description of the Several Views of the Drawings

The concept of Cryogenic Energy Conversion (CEC) is based on the fact that certain semiconductor devices, especially high-voltage power MOSFETs (metal-oxide semiconductor field-effect transistors) work much better when cooled to cryogenic temperatures [M1-M18]. For example, the on-resistance R(on), a major source of loss, is reduced by a factor of 20 to 35 by immersing the devices into liquid nitrogen (T = 400 K / 77 K). **Figure 1** shows the drain current dependence of R(on) for a 1000 V, 33 A MOSFET APT10026JN. Up to a current of 55 A, the on-state voltage or resistance is absolutely stable and constant at 77 K.

In **Figure 2** the measured temperature dependence of R(on) is plotted for a 1000 V, 20 A, 0.53 Ω MOSFET APT10053LNR for drain currents of 1 A, 10 A, and 20 A. Assuming a maximum junction temperature of 100 °C (375 K) for normal operation (300 K), one obtains an R(on) improvement factor of 35 from 375 K to 77 K.

The physics behind CEC is the drastic increase at low temperatures of the majority carrier electron mobility in the drain-drift region of a high-voltage power MOSFET. MOSFETs are the fastest switching power devices available [M8]. For a 100-Hz silicon motor drive, the PWM (pulse-width-modulated) switching frequency of a switch-mode inverter can be low (1 - 20 kHz) so that switching losses are also small or negligible if soft-switching techniques are applied. The maximum efficiency is determined by the ratio of on-state voltage to the voltage swing. The APT MOSFET APT 10050 LVR, rated 1000 V, 21 A, and 0.5 Ω (at 300 K), has an on-resistance of 24.2 mΩ at 77 K, i.e. immersed in liquid nitrogen (LN2). For a supply of 650 V, a current of 10 A, and 2 MOSFETs in series (as is usual in bridge circuits), the on-state voltage to voltage swing ratio is:

$$L = 2\,\frac{0.242\ \mathrm{V}}{650\ \mathrm{V}} = 0.00075$$

This corresponds to a conduction loss efficiency of more than 99.9%. Assuming a cooling penalty of a factor of 10 and negligible switching losses at these low frequencies, an overall ASD inverter efficiency of > 99.0% should be possible. By paralleling more MOSFETs, one can further reduce the losses to any desirable level: "Silicon is cheap"! In addition, one should take into account the "load shedding" property of liquid nitrogen. LN2 can be generated in off-peak

hours.

Another advantage of CEC is the fact that the thermal conductivity of silicon and of MOSFET chip substrates also improves drastically when cryo-cooled [M7]. The basic idea of CEC is to reduce loss from heat directly at the source by cryo-cooling.

Cryo-Multi-Chip Modules (CMCMs)

A conventional motor drive can be large compared to the motor it is designed to operate. Clearly, any reduction in size and weight (and consequently in cost) would be especially advantageous for transportation applications. Multi-Chip Modules have proven to achieve this goal in other industries (most notably aerospace). However, this advantage has not yet been applied to the power electronics industry because of the high power densities involved, which are now reduced by cryo-cooling. By using Multi-Chip Modules optimized for use at cryogenic temperatures, however, the entire volume previously dedicated to cooling systems for the motor drive circuitry can be removed. The resulting reduction in size and weight can be drastic.

Figures 3, 4, and 5 show various embodiments of the Cryo-Multi-Chip Module using the GE-CRD High-Density Interconnect (HDI) technology [11-13].

The proposed cryo-power motor drive will be an important component in the ultimate high-efficiency vehicle (transit bus, ship, truck, etc.), which combines the emerging technologies of high-density interconnects (HDI), fuel cells, HTS electric motors and low-temperature power electronics.

The Cryogenic Electric Fuel Cell Transit Bus: The "Cryo-Bus"

Assuming that a fuel cell as described in the References [2-4] will be available some day in the future, one can envision an electric transit bus as shown in **Figure 6.** A liquid natural gas tank operating at a temperature of 112 K may or may not be surrounded by a liquid-nitrogen tank (77 K), which would act as a protective shield should an accident occur. Thus the Cryo-ASD motor drive can be cooled either by LN2 or by conduction cooling via 'cold pipes' or 'cold fingers' extended directly from the LNG tank. The LNG tank supplies the fuel cell, which in turn generates heat to be used for space heating in the winter months. During the summer, the LNG tank could contribute to space cooling. The electric motors may or may not be implemented using HTS wires or conductors for even smaller size and weight. This invention limits itself to the miniaturization and efficiency optimization of the four motor drives through the application of the concept of CEC using CMCMs or cryo-MOSFETs.

The liquid nitrogen tank may not be necessary and the cryo-power electronics may be located in a hermetically sealed case which is immersed in the cryogenic liquid natural gas. In this case the small losses of the cryo-power electronics would help to evaporate the LNG for use in the reformer of the fuel cell. All cryogenic dewars, tubes, etc. are thermally insulated by multilayer insulation in a high vacuum.

The concept of **Figure 6** also applies, of course, to a bus or vehicle where liquid hydrogen

(LH_2) is used instead of LNG. In this case the cryo-power electronics would be cooled in a space between the LH_2 tank and the ambient at a suitable temperature gradient point in the range of 77 K to 200 K. **Figure 7** shows the details of the cryo-bus enlarged.

A circuit topology as shown in **Figure 8** may be used for the implementation of a cryo-inverter used in combination with the fuel cell. The inverter circuit may be preceded by a boost converter to increase the low output voltage of the fuel cells. In the case where liquid nitrogen is used one can also use liquid oxygen (LOX) produced together with the LN2 for more efficient operation of the fuel cell. In this case it may be possible to eliminate the (necessary) pressurizing of the oxygen supplied to the fuel cell.

H. Detailed Description of the Invention

The key objective of this invention is to apply the concept of cryogenic power conversion to fuel cell-operated electric vehicles and other systems which use either liquid hydrogen {GM car Zafira [1]} or liquid natural gas (LNG) in order to achieve the ultimate in high power conversion efficiency for environmentally friendly transportation. Here, use is made of the fact that the cryogenics is already available and can therefore solve the cooling problem of the cryogenic power electronics plant **8**.

The advantages would be higher efficiency, lower weight, smaller size and lower cost for the required power electronics in a fuel cell-operated vehicle.

The invention is demonstrated in **Figure 7:**

A large vehicle such as a bus **1** uses a fuel cell (FC) **2** which converts oxygen and hydrogen into electrical energy. The wheels **3** are driven by the combination of an adjustable speed motor drive **5** and an electrical motor **6**. The hydrogen needed by the fuel cell **2** can be provided by a liquid hydrogen tank or can be obtained via a reformer from liquid natural gas (LNG, CH4) stored in an LNG tank **8**. The liquid natural gas tank **8** could, of course, also be a liquid hydrogen tank. The latter can be placed inside a larger tank **7** containing liquid nitrogen for additional cool-storage and for protection in case of an accident. The motors **6** could use high-temperature superconducting wires for their windings and can also be cooled by liquid hydrogen or by liquid nitrogen. The cryo-motor drives **5** could be integrated into and with the HTS motors **6** if multi-chip modules are employed.

The cryo-power electronics **5** could also be placed in a hermetically sealed case (not shown), immersed in the LH_2 or LNG tank **8**. The heat generated by the fuel cell **2** can be used for space heating **10** in the bus. The cryo-dewar **8** can also be used for space cooling **9** during the summer. The cryo-motor drives **5** are fed by electrical conductors **12** with a suitable DC voltage. Cables **11** in turn feed electrical power to the motors **6**. These conductors **11** could be high-temperature superconducting (HTS) cables which provide HTS bus motors **6** with electrical power as well as the cooling fluid (LN2). Tube equipment **13** delivers the natural gas or the hydrogen gas to the fuel cell **2**.

The adjustable speed motor drives **5** can be implemented with conventional half- or full-bridge

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